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## FIFTY-HOUR ENDURANCE RUN OF MODEL W-1 ENGINE

(FIRST EXPERIMENTAL MODEL)

(POWER PLANT SECTION REPORT)

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# FIFTY-HOUR ENDURANCE RUN OF MODEL W-1 ENGINE (FIRST EXPERIMENTAL MODEL).

## OBJECT OF TEST.

The object of this test was to determine for developmental purposes the reliability and durability of the model W-1 engine (first experimental model).

## RESULTS.

The operation of the engine while running was good. It was run idling at a speed of 400 revolutions per minute without any irregularity. The acceleration was good throughout the range from idling to full-throttle operation. The fuel and oil consumption were low. The power output varied but little during the test. Considerable oil leakage was apparent throughout the test through the passages in the crank case which accommodated the induction pipes.

There were numerous failures of minor parts and replacements made necessary by excessive wear during the test. However, compared with other first experimental engines, the engine performed remarkably well.

The final failure of the crank case of the first design (see fig. 18), which was inherently weak, caused the test to be discontinued after running 44 hours and 45 minutes.

The general condition of the major parts, with the exception of the crank case, was good. The main bearings and connecting-rod bearings were in excellent condition after a run of this duration. For a detailed description of the engine after test, see "Inspection after test," pages 9 and 10.

## RECOMMENDATIONS.

The following changes in the model W-1 engine are recommended:

### CRANK CASE (UPPER).

The new design which is now being made by the Engineering Division will afford greater strength to this part. A heavier web will be made at that portion of the crank case which accommodates the induction pipes. The web will continue straight back to the wall instead of following the contour of the induction-pipe hole. The opening in the webs which were made to reduce the weight will be made smaller and the webs will be beaded to give greater stiffness.

### CRANK CASE (LOWER.)

Strengthening of the webs similar to that in the upper crank case will also be done in the lower crank case.

### CRANK CASE (PAN).

Provision should be made to allow bolting the carburetor to the crank-case pan rather than to the induction pipes. Provision should be made to prevent oil leakage at the induction pipes.

### CRANK SHAFT.

The oil plugs in the crank shaft should be recessed to obviate the possibility of obstructing the oil holes.

### PROPELLER HUB.

The pitch of the front cone should be made steeper.

### PISTONS.

Provision should be made for better oil drainage by enlarging the oil return holes and recessing under the lower ring.

### CAM-SHAFT ASSEMBLY.

The cam-shaft covers should be stiffened. The cam-shaft housing should be stiffened by means of additional ribbing.

### CYLINDERS.

It is recommended that, in order to assure better alignment of the cam-shaft assembly, the studs should be screwed into the cylinders after welding, instead of before as was done with this engine. The lower portion of the cylinder should be strengthened by making the flange heavier.

### VALVES.

The junction of the head and stem should not be relieved. Provision should be made for putting valve safety wires in the valve stems.

### VALVE GUIDES.

An investigation should be made in an effort to secure better valve-guide material.

### VALVE RETAINING COLLARS.

The valve retaining collars should be strengthened.

### VALVE TAPPETS.

The casehardening on the valve tappet should be deepened.

### COOLING SYSTEM.

The assembly of the water manifold to the cylinders should be simplified. The water pump will be redesigned. The new design will have a shoulder on the impeller shaft supported by a bronze bushing to prevent the impeller scraping the pump case. There will be three outlets on the pump, one of which can handle the water discharge alone while the discharge can be taken care of by the other two when the first is blanked off. A drain plug of new design will be incorporated in the lower part of the pump making it possible to drain the cooling system by screwing off a spanner nut. This nut also provides a seat for a gasket held against the drain passages when screwed up tight.

**CARBURETORS.**

The carburetors should have single venturi equipment.

**ACCESSORY DRIVE BEARINGS.**

The cam shaft, water, and oil pump drive shaft bronze bearings will be replaced by ball bearings.

**TACHOMETER DRIVE.**

The tachometer drive will be taken from the cam shaft and run at cam-shaft speed.

**IGNITION SYSTEM.**

The distributor blocks should be redesigned. There is a tendency in the present design for sparks to jump from one terminal to another. The terminal nuts are too close for practical manipulation in service.

The method of fastening the block is unsatisfactory, as it requires too much side clearance between magnetos.

There is a tendency on the inside of the block for sparks to jump between the segments and the distributor gear. More room may be gained at the bottom of the block by eliminating the felt cam wiper and flattening the top of the breaker cover. This will allow a groove to be turned on the inside between the segments of the larger diameter in the distributor block and the back edge, thus eliminating the tendency to spark.

Greater care should be taken in riveting the breaker contact rivet, also the rivet holding copper grounding strip to the breaker bar.

**INTRODUCTION.**

The model W-1 aviation engine is an 18 cylinder "W" type engine consisting of three banks of six cylinders each, with an included angle of 40 degrees between each bank. It was designed by the Engineering Division. The bore is  $5\frac{1}{2}$  inches and the stroke  $6\frac{1}{2}$  inches. The cylinders are steel forgings with a welded water jacket of sheet-steel stampings. There are four valves per cylinder. The valves are operated by overhead cam shafts through rocker arms. The cylinders are mounted separately on the crank case and are held down by means of six studs and nuts for each cylinder, one of the studs being common to two cylinders. Ignition is furnished by three magnetos mounted on the rear of the engine. The carburetion is furnished by six single carburetors mounted underneath the engine, three on a side.

Where reference is made to the right or left bank the point of observation is assumed as the pilot's seat. The cylinders are numbered from the antipropeller end.

Two views of the engine assembly may be found in figures 1 and 2.

**METHOD OF CONDUCTING TEST.**

Preliminary power runs were made on this engine and reported in a memorandum from the engineer in charge, power plant laboratory to the chief, power plant section, under date of May 17, 1921.

This test was conducted at McCook Field, Dayton, Ohio. The engineer conducting the test was J. R. Walsh. The test was begun March 28, 1921, and was completed May 6, 1921.

Prior to mounting on the torque stand the engine was given preliminary calibration runs on the dynamometer. These runs consisted of a full-power calibration run with a carburetor setting limiting the power output to 700 horsepower at 1,700 revolutions per minute, a friction horsepower run, a propeller load run, and a run to determine the maximum and minimum heads of gasoline at which the engine would function. The same setting was used during the endurance run.

The engine was then mounted on a torque stand in the open air and fitted with a propeller absorbing the full power of the engine at the normal speed of 1,700 revolutions per minute.

The 50-hour endurance run was divided into 10 periods of 5 hours each. The first half hour of each 5-hour period was run at full throttle. During the remaining  $4\frac{1}{2}$  hours the engine was run at nine-tenths power at 97 per cent of the full-throttle speed as determined by the propeller characteristics. Between each 5-hour period a stop was made and the engine given a careful external inspection.

At the start of the test, the propeller was bolted to the engine hub, balanced and tracked. The engine was thoroughly cleaned externally. The gasoline and oil lines were checked. The spark, throttle, and mixture control were checked to insure maximum movement. At the beginning of each period the lubrication system was filled with warm oil, the engine was turned over several times, primed and started immediately. It was run throttled under 1,000 revolutions per minute until the oil had reached a temperature of  $100^{\circ}$  F.

During the test, note was made of all difficulties encountered. At 15-minute intervals the following readings were taken:

Revolutions per minute (by counter).

Oil temperature.

Oil pressure.

Water temperature (entering and leaving cylinders).

Manifold vacuum.

Atmospheric pressure (barometer).

Fuel consumption.

Oil consumption.

Air temperature.

The fuel and oil consumption was obtained by reading the supply scales at 15-minute intervals.

The data obtained at 15-minute intervals were computed into hourly averages. An exception was made, however, for the one-half hour runs at full throttle, and for discontinuous runs of less than an hour duration, which were averaged separately.

Owing to the many variable errors in the use of the ordinary cradle stand and absorption propeller for measuring torque reaction, the power output was computed by the method described below.

The assumption is made that during the first half hour run on the torque stand, the engine will develop the same power that it did at the corresponding speed on the dynamometer. The horsepower developed during the first half hour on the torque stand was therefore obtained from the dynamometer power curve. The point thus obtained was taken to be a point on the power absorption curve of the propeller, and a curve conforming to the cube law of power-speed relation was therefore drawn through this point. (See fig. 6.) The power developed by the

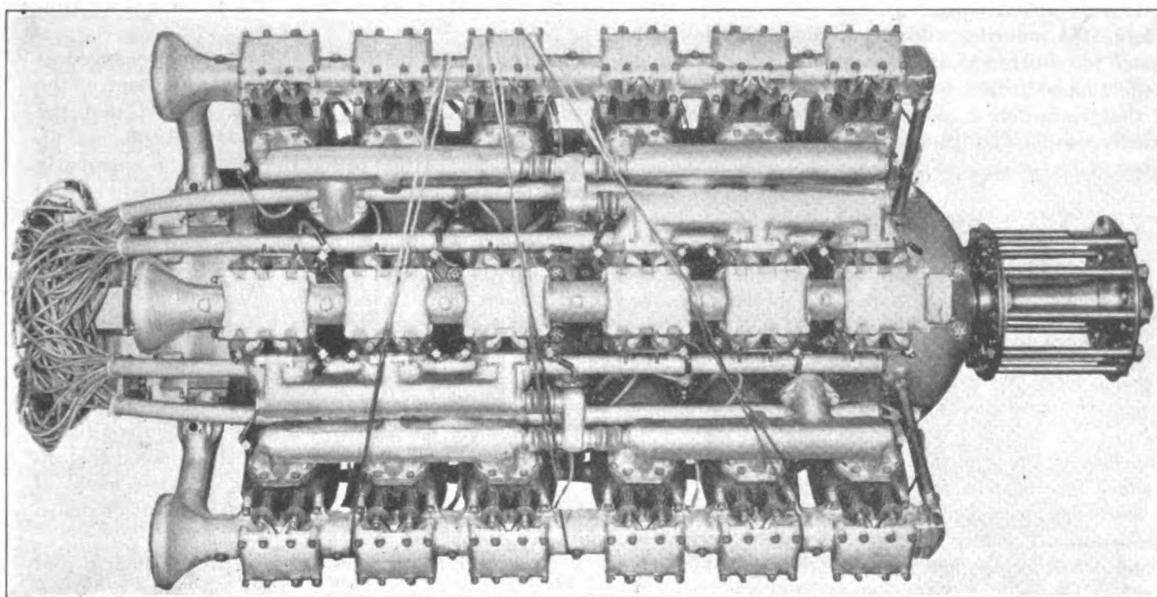


FIG. 1.—Plan view.

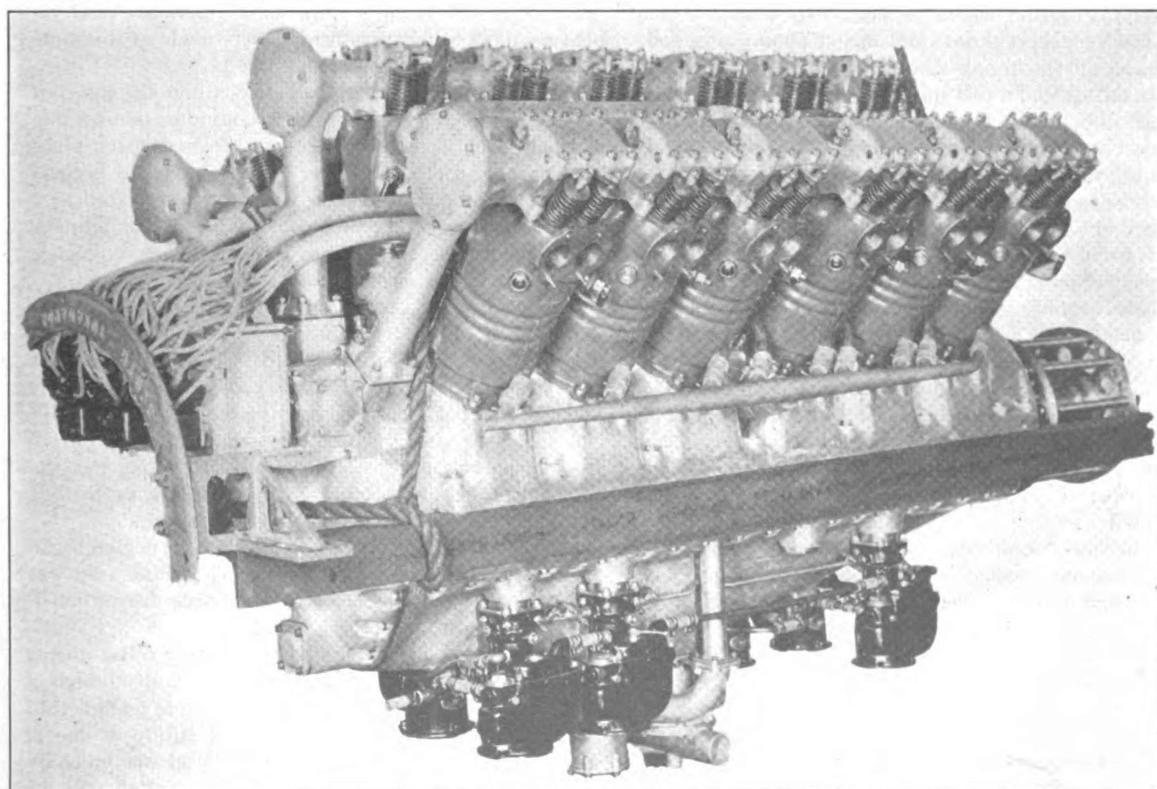


FIG. 2.—Right rear three-quarter view.

engine at any time subsequent to the first half hour was taken directly from this curve.

In using the propeller calibration curve no allowance was made for differences in atmospheric conditions and their effect on propeller characteristics, since it has been found that variations in power due to these differences are usually smaller than the error due to changes in wind direction and velocity.

#### ANALYSIS.

Dynamometer test results and summarized results by hourly averages of the 50-hour run are included in the data sheets, pages 15 to 17. With varying fuel head on the dynamometer the operation was regular at heads from 1 foot to 16.5 feet. With a head of 0.5 foot the operation was irregular. Best power was obtainable with a head of 7 feet.

While making the preliminary runs on the dynamometer the bronze bearings, in which the water and oil pump drive shafts run, were burnt out (see fig. 10) due to lack of lubrication. The only lubrication supplied to them at that time was the overflow from the cam-shaft housing. When the bearings were replaced provision was made for supplying direct lubrication to these bearings and no further trouble was encountered throughout the test. In the improved design the bronze bearings will be replaced with ball bearings.

Considerable trouble was experienced with the water pump while running the engine on the dynamometer. The bronze button which supported the impeller shaft wore in a very short time sufficiently to allow the impeller to scrape on the pump case. (See fig. 11.) A second bronze button and a cast-iron button also wore badly and similar difficulty was experienced. Substitution of a lignum-vitae button solved the difficulty.

During the first 10 hours on the torque stand the only trouble encountered was with spark plugs. At the end of the second 5-hour period all the spark plugs were tested. It was found necessary to replace four spark plugs. Three of them had broken porcelains, while the other was fouled.

The first serious trouble occurred 1½ hours after starting the fourth 5-hour period. At that time a spring-retaining collar of the front intake valve of No. 6 cylinder right bank failed, allowing the valve to drop into the cylinder. As a result the piston was badly battered and broken. A portion of the valve stem was drawn through the induction header and lodged under the intake valve of No. 4 cylinder. No. 6 cylinder was badly damaged and was replaced.

At the time No. 6R cylinder was removed an inspection of the crank case was made through the opening into which the cylinder sleeve passes. It was observed that the web in the upper and lower crank case supporting No. 6 bearing was cracked vertically on each side for its whole depth at the fillet made by the induction passage and the web proper. It was thought that no serious damage would result from further running in this condition, as the crank case was probably cracked after the dynamometer runs, so the test was resumed.

A stop was made three-quarters of an hour later, after 17½ hours' running, when the tachometer drive-shaft key sheared.

A slight water leak was detected in the water jacket of No. 4R cylinder under the cam-shaft housing after running 24½ hours.

The spark plugs in No. 3R cylinder were changed at the end of the sixth 5-hour period. At the end of the seventh 5-hour period an inspection showed that the compression had become poor in No. 4R, 5R, 6R, and 6L cylinders. During this period the engine was apparently getting too lean a mixture even with the altitude control in the full rich position. It was found that several of the valve guides had become badly worn and contributed largely to the poor mixture in the cylinders. Further investigation showed a number of minor failures for which repairs and replacements were necessary. A summary of these changes will be found on page 17.

An inspection made after 38 hours running indicated that the engine required further replacements. Reference to the summary on page 17 will give an itemized list of the changes made at this time. It will be noted that all the outer valve springs on the right and left banks of cylinders were changed to standard Liberty exhaust springs.

Eighteen minutes after starting the ninth 5-hour period trouble was detected in the engine operation. An investigation showed that there was a water leak into No. 1 cylinder. The cylinder was removed and a crack about 4½ inches long was found at the welded junction of the cylinder head and barrel. A sectional photograph of the cylinder (see fig. 16) shows clearly the method of constructing the cylinder. The crack referred to was very fine. It is not visible in the photograph. Several replacements of minor parts which were made at this time will be found in the summary on page 17.

Two attempts were then made to continue the test, but the engine was stopped after a few minutes running due to trouble in the ignition system. Several spark plugs were changed and the breaker point, which had become loose on the center magneto breaker arm, was replaced.

A valve spring retaining collar failed a few minutes after the next start was made. In this instance no damage was done to the piston or cylinder.

Another start was made, but after running 15 minutes a drop in speed of 150 revolutions per minute necessitated a stop. It was found that the small venturi tube bracket in the front left carburetor broke at a sharp fillet (see fig. 17) and distorted the main discharge nozzle.

A half hour after the next start an identical failure of the bracket occurred on the same carburetor, but the discharge nozzle was unhurt. A water leak in No. 2R cylinder water jacket was detected at this time.

After running 45 hours and 45 minutes the engine began to weave badly and was stopped. The crank case was found to be so badly cracked that the test was discontinued. (See figs. 18 and 19.)

The failure of the valve spring retaining collar during the fifth 5-hour run was evidently due to faulty design of this part. The section at the point of failure was too thin and had a sharp corner. The second failure of one of these parts occurred at the same point and was probably due to the same cause. The retaining collar will be strengthened.

Excessive wear of valve guides occurred frequently during this test. In all 14 replacements were made. A

metallurgical analysis of the valve guides showed that they were made of material which was practically the same as has been successfully used with the Liberty engines. Wear is attributed to stress of service. None of the valve guides in the center bank were replaced. The weak crank case evidently allowed considerable weaving in the right and left banks. In the photographs (figs. 12 and 13) No. 1 had run only 3 hours. The other valve guides had been run for 35 hours.

Valve-spring trouble persisted throughout the run. A metallurgical analysis of the original springs showed them to be of plain carbon steel, which is considered unsuitable for springs of this kind. A large amount of manganese sulphide was present in the steel and may have been a contributory cause to the failures. However, after all the outer springs on the right and left banks had been replaced with standard Liberty exhaust springs, six of these were broken in the following 2 hours and 18 minutes. The Liberty engine springs are made to accommodate a larger valve than those used in the model W-1 engine and stand slightly higher spring pressures. It would seem, therefore, that the valve spring failures might be due to the sharp cam action (quick opening and closing of the valves) or to the weaving of the engine due to the cracked crank case.

It was necessary to replace 13 inlet valve tappets during the run because of excessive wear. The excessive wear of the valve tappets can be attributed to the thin case obtained during the hardening process.

#### INSPECTION AFTER TEST.

##### CRANK CASE (UPPER).

The upper crank case was badly cracked in front and under the first three cylinders in each bank. The cracks were interconnecting between the flanges and extended vertically in the webs at the induction-pipe opening. The hollow box web under the center main bearing was cracked and had a depression and thin section on the gear side of the web due to poor casting. The case was chafed at the parting flange. One cylinder to crank-case stud between 4C and 5C and one at the front of 6C were broken. (See fig. 18.)

##### CRANK CASE (LOWER).

The webs under cylinders Nos. 4 and 5 and between Nos. 5 and 6 cylinders were cracked all the way through. The case was chafed at the parting flange. The bearing backing was chafed. (See fig. 19.)

##### CRANK SHAFT.

The crank shaft was out of line 0.012 inch at the center bearing.

##### PROPELLER HUB.

The rear cone and the propeller hub surface on the rear cone were galled.

##### CONNECTING RODS.

The connecting rods were in good condition. They showed the usual amount of heat at the small end bearing.

##### MAIN BEARINGS.

All bearings were slightly scratched. Lower bearings numbers 2, 4, 5, 6, 7, and 8 showed uneven wear and the backs of the shells were chafed. In general, the bearings were in excellent condition. (See figs. 21 and 22.)

##### CONNECTING-ROD BEARINGS.

All the connecting-rod bearings were in excellent condition. (See figs. 23 and 24.)

##### PISTONS.

Numbers 1R, 2R, 3R, 4R, and 5R pistons had a fairly heavy carbon deposit on the piston head. There was no deposit inside the pistons underneath the head. All the pistons showed wear on the top land. The rings were all free in their grooves. The pistons showed no signs of erosion. The piston skirts were all oil burnt on the anti-thrust side. There were no "blow-bys." There was no appreciable wear in the piston bosses. (See figs. 25, 26, and 27.)

##### CAM-SHAFT HOUSING (LEFT BANK).

The cam-shaft housing was porous at 1, 3, 4, and 5 cylinders. The surfaces on the housing under rocker covers Nos. 3 and 4 were chafed. The rocker bearings showed the usual wear. The housing feet were broken at Nos. 1 and 5 cylinders. (See fig. 20.)

##### CAM-SHAFT HOUSING (CENTER BANK).

The rocker bearings showed the usual wear. One housing foot at No. 6 cylinder was cracked. There were a few porous spots near No. 4 rocker bearing.

##### CAM-SHAFT HOUSING (RIGHT BANK).

There were porous spots near Nos. 1, 3, 5, and 6 cylinders. The rocker bearings showed the usual wear.

##### CAM SHAFTS.

The cam shafts were in good condition.

##### CAM-SHAFT BEARINGS.

The cam-shaft bearings were in good condition.

##### ROCKER ARMS (RIGHT BANK).

All rocker journals showed slight wear and Nos. 1 and 5 were slightly rusted. The valve tappets of Nos. 1, 5, and 6 cylinders were worn excessively.

##### ROCKER ARMS (LEFT BANK).

There was slight wear on the journals of Nos. 1, 2, and 3 rocker arms. The journals of No. 6 rocker arms were badly worn. Nos. 1, 4, and 5 valve tappets were badly worn.

##### ROCKER ARMS (CENTER BANK).

All the journals were slightly worn. Nos. 2, 3, and 4 were rusted. No. 6 inlet valve tappets were badly worn.

##### CAM-SHAFT COVERS (RIGHT BANK).

Both bearing surfaces of Nos. 1, 4, and 5 rocker covers were scored. The bearing nearest the intake valve of Nos. 2 and 3 was scored.

**CAM-SHAFT COVERS (LEFT BANK).**

The bearings nearest the inlet valve of Nos. 3 and 5 rocker covers were scored. Both bearings of Nos. 1, 4, and 6 were scored.

**CAM-SHAFT COVERS (CENTER BANK).**

Both bearings of Nos. 1, 2, 3, 4, and 5 were scored slightly. The bearing nearest No. 6 intake valve was slightly scored.

**GEARS.**

The gear driving the water pump showed uneven wear from improper cutting. The pinions driving the cam shaft were excessively worn. In general the gears showed the usual wear for a run of this duration.

**VALVE GUIDES.**

All the valve guides on the right and left banks were badly worn. No. 3L front inlet valve guide was broken through its diameter at the junction of the valve guide flange and the cylinder.

**VALVES (LEFT BANK).**

The front exhaust valves of Nos. 1, 4, and 5 cylinders showed signs of excessive heat, as did both exhaust valves in Nos. 2, 3, and 6 cylinders. All valves had excessive play in guides. Nos. 1, 2, and 3 inlet valves had heavy carbon deposits on the upper side. Both inlet valves in Nos. 1, 2, 3, and 6 cylinders leaked slightly, as did both exhaust valves in Nos. 2, 4, and 5 and the rear exhaust valves in Nos. 1 and 6. No. 3 exhaust valves leaked badly. (All valves were tested with gasoline for leakage.)

**VALVES (RIGHT BANK).**

All the exhaust valves showed signs of excessive heat. Nos. 2 and 5 rear exhaust valves were scaled. Nos. 1, 2, 3, and 5 intake valves had a heavy carbon deposit on the upper side of the valve head. Both inlet valves in Nos. 1 and 2 cylinders leaked slightly, as did Nos. 4 and 6 exhaust valves. No. 1 front and No. 3 rear exhaust valves also leaked slightly. Both exhaust valves in Nos. 2 and 5 cylinders leaked badly. All the valves were loose in their guides.

**VALVES (CENTER BANK).**

Nos. 1, 2, 3, 4, 5, and 6 exhaust valves showed signs of excessive heat. Nos. 2, 3, and 6 exhaust valves were badly pitted and scaled. No. 3 front exhaust valve was particularly bad, having a portion of the valve head burnt away. All the valves were loose in their guides. Both intake valves in Nos. 2, 3, 4, 5, and 6 and both exhaust valves in Nos. 1, 4, and 5 leaked slightly. Both exhaust valves in Nos. 2, 3, and 6 leaked badly.

**VALVE SPRINGS.**

Five intake and 12 exhaust springs were found broken after the test. One of the exhaust springs, an inner spring, was the only spring found broken on the center bank after the test.

**VALVE-SPRING COLLAR KEYS.**

A number of the valve-spring collar keys were badly worn.

**CYLINDERS (LEFT BANK).**

The exhaust valve seat of No. 2 cylinder was badly pitted. There was a leak in the water jacket on the head of Nos. 6, 5, 4, and 2 cylinders.

**CYLINDERS (RIGHT BANK).**

All the valve seats were slightly pitted in Nos. 1 and 3 cylinders. Both exhaust valves were badly pitted in Nos. 2 and 5 cylinders. There was a leak in the water jacket of No. 2 cylinder.

**CYLINDERS (CENTER BANK).**

The intake valve seats of Nos. 2 and 4 cylinders were slightly pitted. Both exhaust valve seats in No. 2 cylinder were badly pitted. The front exhaust valve seat of No. 3 cylinder was badly pitted. All intake and exhaust valve seats in No. 5 cylinder were slightly pitted.

**LUBRICATION SYSTEM.**

A flange on the oil manifold was broken.

**WATER PUMP.**

The lower case and impeller were badly worn by rubbing early in the test. The shaft was slightly rusted. (See fig. 11.)

**CARBURETION.**

The carburetors were in good condition. Replacements of two small venturi brackets had to be made on one of the carburetors shortly before the test was discontinued. The needle valves and seats showed the usual wear.

**IGNITION.**

The high-tension coil of the right magneto was punctured.

All other parts were in good condition.

**TOTAL REPLACEMENTS DURING 50-HOUR TEST.**

Cylinders.....	2
Valve springs:	
Intake.....	31
Exhaust.....	28
Valve guides:	
Intake.....	7
Exhaust.....	7
Valves (replaced):	
Intake.....	3
Exhaust.....	6
Valves (ground):	
Intake.....	20
Exhaust.....	20
Spark plugs:	
Cracked porcelains.....	16
Fouled.....	16
Valve spring retaining collar.....	2
Venturi tube bracket (carburetor).....	2
Main discharge nozzle (carburetor).....	1
Magneto.....	1
Magneto breaker.....	1
Valve tappets (inlet).....	13
Pistons.....	1
Tachometer adapter drive shaft.....	2





FIG. 4.

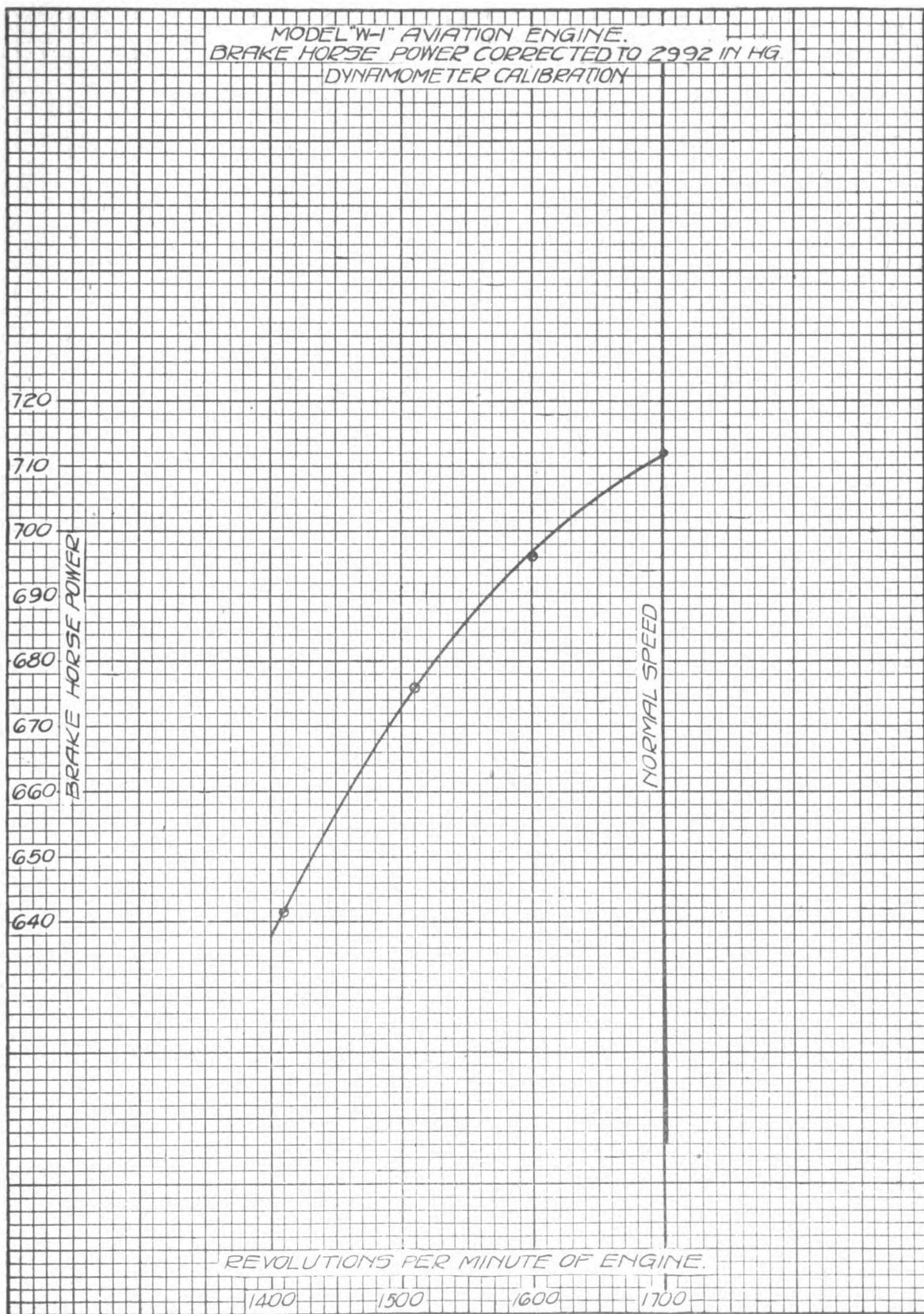


FIG. 5.

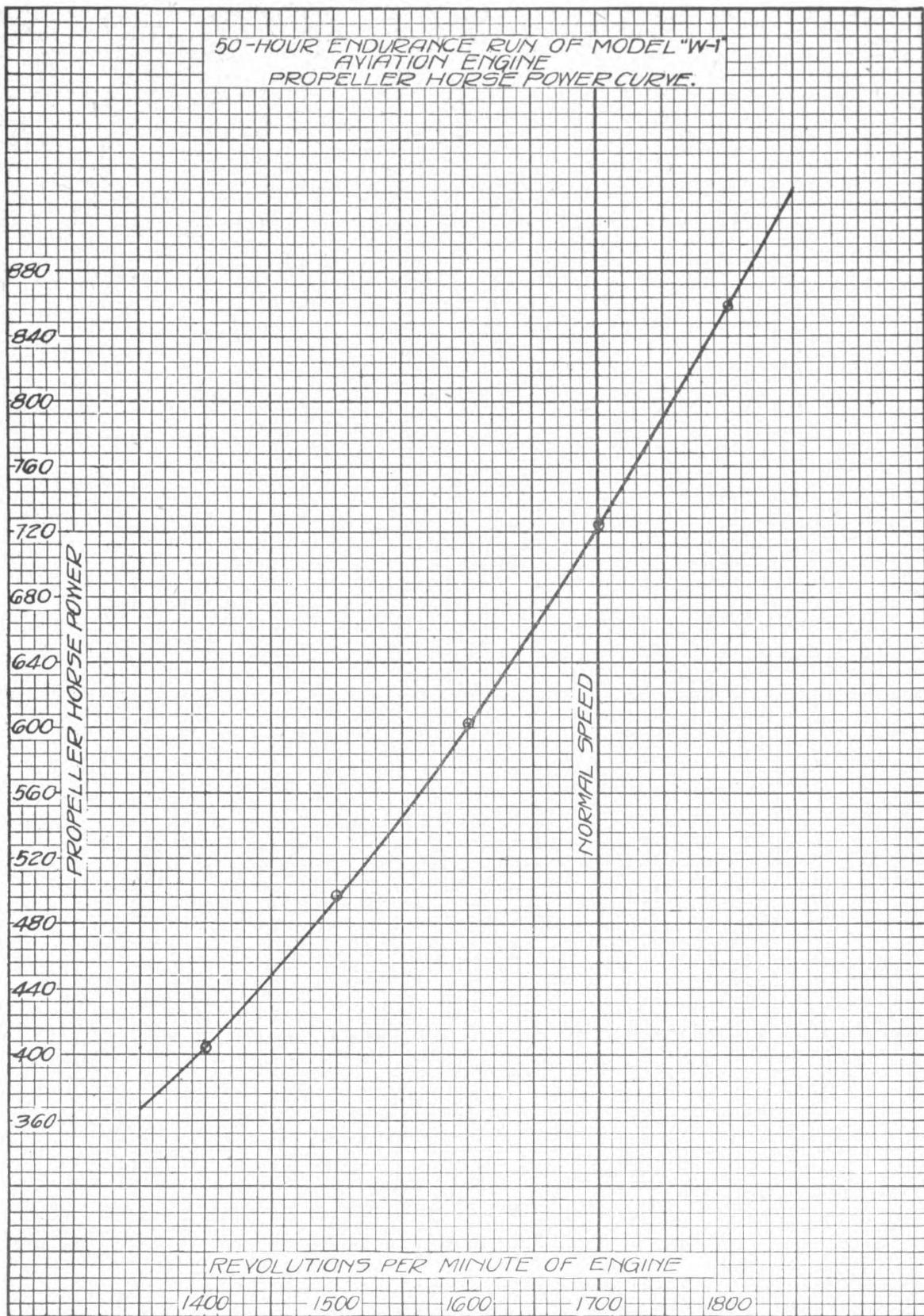


FIG. 6.

*Full power run.*  
(CALIBRATION ON DYNAMOMETER.)

R. P. M.	Actual.		Corrected.			Water.		Oil.			Carb. air temp., ° F.	Man. vac. in. hg.	Carb. vac. in. hg.	Gas cons.		
	Brake load, lb.	B.H.P.	Torque, lb.-ft.	H. P.	B. M. E P., lb. per sq. in.	Temp., ° F.	Temp., ° F.	Press., lb. per sq. in.	Press., lb. per sq. in.				Sec. for 9 lb.	Lb. per hp. hr.		
						In.	Out.		In.	Out.						
1,410	1,342	631	2,387	641.4	129.5	146	170	100	130	78	65	50	1.8	0.5	97.4	0.528
1,510	1,321	665	2,350	676.0	127.5	144	170	100	130	75	65	50	2.0	.5	95.0	.513
1,600	1,284	685	2,283	696.0	123.8	148	170	100	136	76	62	49	2.2	.6	94.6	.500
1,700	1,234	700	2,196	712.0	119.2	146	170	104	144	76	62	48	2.3	.6	112.0	.505

Carburetor setting: Chokes,  $\frac{1}{4}$  inches; main jets, No. 44 drill; brake arm, 21 inches; kind of oil used, 50 per cent U. S. Spec. 3501, 50 per cent No. 3550; average barometer, 29.43 in. hg.

NOTE.—The carburetor throttles were adjusted to give 700 horsepower at 1,700 revolutions per minute.

March 28, 1921.

*Daily log of run.*

TABLE OF AVERAGE RESULTS.

Date.	Time.				R. P. M.	B. H. P. from curve.	Carb. air temp., ° F.	Baro., in. hg.	Water.		Oil.		Man. vac., in. hg.	Carb. vac., in. $H_2O$	Fuel cons.		Oil cons. (Lb. per hr.)				
	Total elapsed.		Duration this run.						Temp., ° F.	Temp., ° F.	Press., lb. per sq. in.	Man. vac., in. hg.			Lb. per hr.	Lb. per hp. hr.					
	Hour.	Min.	Hour.	Min.					In.	Out.	In.	Out.			In.	Out.					
Apr. 11, 1921	0	1 30	0	30	1,680	708	41	29.44	164	171	112	139	73	2.0	10.9	366.0	0.517	10.8			
	1	00	0	30	1,637	644	42	29.44	164	170	110	137	76	2.8	9.8	320.0	.497	9.8			
	2	00	1	00	1,633	639	43	29.46	164	170	114	138	77	2.5	10.9	321.7	.509	8.7			
	3	00	1	00	1,644	652	45	29.42	164	170	116	139	75	2.4	10.5	331.3	.508	8.3			
	4	00	1	00	1,644	652	47	29.42	164	170	118	139	73	2.6	9.7	320.7	.492	7.7			
	5	00	1	00	1,640	648	49	29.36	164	170	110	137	71	2.6	9.4	320.3	.494	6.8			

No. 1 stop.—End of first 5-hour period.

Apr. 12, 1921	5	1 20	0	30	1,681	697	46	29.23	161	170	113	138	76	2.2	8.2	350.0	.502	6.2
	6	00	0	30	1,639	617	51	29.23	164	170	112	138	75	2.7	13.7	310.0	.526	7.4
	7	00	1	00	1,638	643	54	29.29	165	170	113	139	76	2.7	20.4	377.6	.588	7.3
	8	00	1	00	1,635	612	57	29.15	165	170	113	139	73	2.7	19.4	370.5	.577	7.4
	9	00	1	00	1,641	649	60	29.12	165	170	116	141	69	2.9	14.0	332.0	.510	7.2
	10	00	1	00	1,631	637	59	29.13	165	170	118	141	73	2.6	18.8	337.3	.530	7.9

No. 2 stop.—End of second 5-hour period. Spark plugs in No. 2L cylinder, inlet side; 3L cylinder, exhaust side, and 1R cylinder, exhaust side, had broken porcelains. The spark plug in No. 5L cylinder, exhaust side, was fouled. They were all replaced with new plugs.

Apr. 13, 1921	10	1 30	0	30	1,682	698	68	29.00	166	170	117	145	77	2.5	14.1	332.5	.477	10.6
	11	00	0	30	1,651	661	69	29.00	166	170	120	147	72	2.8	10.7	312.0	.472	8.4
	12	00	1	00	1,647	656	71	29.00	165	170	120	147	70	2.7	15.6	313.7	.478	8.5
	13	00	1	00	1,627	632	71	29.00	165	170	120	143	78	2.9	9.6	290.0	.459	9.1
	14	00	1	00	1,640	618	73	29.00	164	170	123	146	79	2.8	9.9	285.0	.455	8.7
	15	00	1	00	1,636	612	73	29.00	164	170	121	146	75	2.7	10.5	296.0	.461	8.9

No. 3 stop.—End of third 5-hour period.

<sup>1</sup> Full throttle.

<sup>2</sup> Gasoline drain leaked.

Apr. 14, 1921	15	1 30	0	30	1,700	722	66	28.74	163	170	120	146	83	2.4	16.0	367.0	.508	10.6
	16	00	0	30	1,647	656	64	28.74	164	170	122	145	79	3.3	11.8	291.0	.444	7.6
	16	45	0	45	1,640	648	64	28.76	164	170	119	144	77	2.7	10.9	292.5	.452	8.9

No. 4 stop—Valve-spring collar failed, allowing front intake valve of No. 6R cylinder to drop in on the piston, breaking valve and damaging piston and cylinder. A new piston and cylinder complete were installed. The front outside intake valve spring of No. 5R cylinder was broken. It was replaced. All the valves in No. 5R cylinder were ground.

Apr. 18, 1921	17	00	0	15	1,652	663	54	29.18	164	170	126	141	86	2.6	9.3	312.0	.471	10.8
	17	30	0	30	1,641	649	56	29.18	163	170	129	142	87	2.8	8.5	307.0	.473	8.6

No. 5 stop—Tachometer adapter drive-shaft key sheared. Replaced with new adapter.

Apr. 19, 1921	18	00	0	30	1,632	638	56	29.18	164	171	121	133	68	2.9	8.7	293.0	.460	8.4
	19	00	1	00	1,634	640	58	29.18	163	170	127	140	71	2.8	9.0	298.0	.466	8.0
	20	00	1	00	1,632	638	57	29.16	164	170	128	140	68	2.7	10.9	307.0	.481	7.2

No. 6 stop—End of fourth five-hour period.

<sup>1</sup> Time for 11 pounds.

## Daily log of run—Continued.

TABLE OF AVERAGE RESULTS—Continued.

Date.	Time.				R. P. M.	B. H. P. from curve.	Carb. air temp., ° F.	Baro., in. hg.	Water.		Oil.		Man. vac., in. hg.	Carb. vac., in. H <sub>2</sub> O.	Fuel cons.		Oil cons. (l.b. per hr.)	
	Total elapsed.		Duration this run.						Temp., °F.	Temp., °F.	Press., lb. per sq. in.	In.	Out.	In.	Out.	Lb. per hr.	Lb. per hp. hr.	
	Hr.	Min.	Hr.	Min.					In.	Out.								
Apr. 19, 1921.	20	1 30	0	30	1,711	737	58	29.17	164	170	131	147	71	1.8	8.3	361.0	.490	9.2
	21	00	0	30	1,640	648	60	29.17	163	170	131	145	73	2.8	7.1	287.0	.443	7.6
	22	00	1	00	1,628	632	62	29.17	163	170	130	144	73	2.8	7.3	286.0	.453	7.9
	23	00	1	00	1,639	646	65	29.13	164	171	130	145	72	2.5	7.4	298.3	.462	7.7
	23	45	0	45	1,638	645	65	29.14	164	170	131	145	67	2.4	7.0	299.5	.465	7.4

No. 7 stop—Tachometer adapter drive-shaft key sheared. Replaced with new adapter.

Apr. 19, 1921.	24	00	0	15	1,632	638	68	29.14	164	171	127	143	69	2.5	5.0	292.0	.457	8.6
	25	00	1	00	1,638	645	67	29.12	163	170	131	145	68	2.4	5.0	298.3	.463	9.3

No. 8 stop—End of fifth 5-hour period. After running 4½ hours of this period a water leak was detected in the water jacket of No. 4R cylinder under the cam shaft.

Apr. 20, 1921.	25	1 30	0	30	1,709	734	71	29.00	163	170	125	148	71	1.5	9.2	362.0	.493	8.8
	26	00	0	30	1,643	651	72	29.00	163	170	132	151	72	2.5	7.2	290.0	.446	9.8
	27	00	1	00	1,634	640	72	29.00	164	170	133	150	72	2.5	7.1	290.3	.454	9.0
	28	00	1	00	1,639	646	70	29.12	163	170	135	149	70	2.5	7.3	294.3	.456	8.3
	28	30	0	30	1,641	649	71	28.95	163	170	133	150	71	2.6	7.5	292.5	.452	8.0

No. 9 stop—End of day.

Apr. 21, 1921	29	00	0	30	1,651	663	58	28.87	163	170	135	148	70	2.6	9.4	316.5	.477	11.0
	30	00	1	00	1,631	637	61	28.88	163	170	133	149	71	2.5	7.4	297.0	.466	8.1

No. 10 stop—End of sixth 5-hour period. Spark plugs in No. 3R cylinder replaced. Broken porcelains.

Apr. 21, 1921	30	1 30	0	30	1,696	704	63	28.88	163	170	128	147	68	1.9	7.1	364.5	.518	5.4
	31	00	0	30	1,633	640	65	28.88	163	170	133	150	68	2.5	5.4	285.0	.446	8.0
	32	00	1	00	1,635	641	66	28.88	163	170	133	150	67	2.5	5.2	292.3	.456	7.3
	33	00	1	00	1,632	639	66	28.87	164	171	133	150	66	2.5	4.8	292.0	.457	7.7
	34	00	1	00	1,637	644	67	28.86	163	170	128	150	70	2.5	4.7	294.7	.458	6.9
	35	00	1	00	1,638	645	68	28.88	164	170	135	152	68	2.4	4.8	301.7	.468	8.0

No. 11 stop—End of seventh 5-hour period. After this run all the valves in Nos. 4R, 5R, 6R, and 6L cylinders were ground. One broken exhaust valve spring (outside) in No. 4R cylinder and one in No. 5R were replaced. One inlet valve spring in each of cylinders 1R, 4C, and 6R were broken. One intake valve guide in No. 6R was broken. Two exhaust valve guides in No. 5R cylinder were badly worn and were replaced, as were two intake valve guides in No. 6R and two exhaust valve guides in No. 6L cylinder. (See figures 12 and 13.) The water jackets under the cam shaft in No. 4R and No. 2L cylinders were welded. A new gasket was put under No. 6L cylinder. No. 6L rear exhaust valve was badly burnt. It was replaced. The left magneto was changed. It had an open circuit in the coil. One spark plug in each of the following cylinders had cracked porcelains: 1L, 2C, 4R, 5C, 5L, and 6R. All the plugs in No. 4L were oil soaked.

Apr. 27, 1921	35	1 30	0	30	1,653	664	62	29.00	160	170	116	143	71	1.9	6.5	242.5	.365	8.2
	35	45	0	15	1,625	629	62	29.00	161	170	130	146	78	2.4	3.8	307.0	.488	8.0

No. 12 stop.—Air in gasoline line.

	36	00	0	15	1,613	616	62	29.00	162	171	121	142	63	2.7	4.7	288.0	.468	5.6
	37	00	1	00	1,611	612	65	28.99	161	170	129	146	66	2.7	4.0	283.0	.463	7.7
	38	00	1	00	1,612	613	65	28.99	162	170	131	147	71	2.7	3.8	284.3	.464	6.6

No. 13 stop.—End of day.

After this run several valve guides which were worn badly were replaced as follows: Rear exhaust valve guides No. 3R and No. 4L cylinders, rear inlet valve guide No. 5L and front exhaust valve guide in No. 6L cylinders (See fig. 12). All the outer springs on the right and left banks were replaced with standard Liberty exhaust springs. All the valves in Nos. 3R, 5R, 4L, 5L, and 6L cylinders were ground. One exhaust valve in No. 3R cylinder was badly burnt. It was replaced with a new valve. The front inlet valve tappets in Nos. 1R, 1L, 2L, 3L, 5L, and 6L cylinders were badly worn and replaced, as were both inlet tappets in Nos. 4L, 3R, and 6R cylinders and the rear inlet tappet in No. 5R cylinder (See fig. 14). All the tappet clearances on the right and left banks were reset.

Apr. 30, 1921	39	00	1	00	1,623	628	47	29.13	163	170	132	146	72	2.5	10.3	355.3	.566	7.8
	40	00	1	00	1,639	646	52	29.15	163	170	130	147	73	2.4	10.4	354.3	.549	7.6

No. 14 stop.—End of eighth 5-hour period.

1 Full throttle.

## Daily log of run—Continued.

TABLE OF AVERAGE RESULTS—Continued.

Date.	Time.				R. P. M.	B. H. P. from curve.	Carb. air temp., °F.	Baro., in. hg.	Water.		Oil.		Man. vac., in. hg.	Carb. vac., in. H <sub>2</sub> O.	Fuel cons.		Oil cons. (Lb. per hr.)			
	Total elapsed.		Duration this run.						Temp., °F.	Temp., °F.	Press., lb. per sq. in.	Lb. per hr.			Lb. per hp. hr.					
	Hr.	Min.	Hr.	Min.					In.	Out.	In.	Out.								
May 2, 1921	40	15	0	15	1,680	696	43	.....	162	171	133	145	66	1.9	3.0	346.0	.497	4.		

No. 15 stop.—Water leak at weld between cylinder head and barrel of No. 1C cylinder. (See fig. 16.) The cylinder was replaced with a new one. The front intake valve guide in No. 4R and both intake valve guides in No. 5R cylinders were badly worn and replaced. (See fig. 12.) The following outer valve springs were broken: No. 3R (front exhaust) 5L (rear intake), 6R (rear exhaust), 5R (both intake). Nos. 4R and 5R exhaust valves were burnt. They were replaced. One cylinder stud between 5R and 6R cylinders was broken.

May 3, 1921. An attempt was made to complete the run, but after running a few minutes a stop was made because of fouled spark plugs in Nos. 4L, 5L, and 6L cylinders. The plugs were replaced and the engine again started. While warming up the engine No. 4L rear intake valve spring retaining collar failed. The valve and spring retaining collar were replaced.

May 4, 1921	40	145	0	30	1,696	717	60	28.97	164	170	124	144	60	2.0	6.2	386.0	.538	10.0
	41	00	0	15	1,659	670	59	28.97	164	170	132	149	62	2.4	4.8	.....	.....	8.8

No. 16 stop.—Power decreased and speed fell off about 150 revolutions per minute. It was found that the small venturi tube bracket of the front left carburetor was broken. The main discharge nozzle was distorted. The spark plug-porcelains in Nos. 1R (two plugs), 5L (rear), 5R, 1L, 3L, and 5C (front) were cracked. The three spark plugs in 5C were fouled. The breaker point on the center magneto breaker arm was loose. It was replaced with a new breaker.

May 5, 1921.	41	30	0	30	1,635	641	71	28.95	164	170	135	155	70	2.5	2.0	284.5	.444	7.2
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No. 17 stop.—Small venturi tube bracket of front left carburetor failed.

May 6, 1921.	42	30	1	00	1,634	640	65	29.01	164	169	131	151	71	2.4	4.5	318.7	.498	9.3
	43	30	1	00	1,620	624	69	29.01	164	170	133	152	70	2.4	3.0	300.7	.482	7.7
	44	30	1	00	1,623	627	70	29.00	163	169	138	154	73	2.3	2.3	296.3	.473	10.3
	44	45	0	15	1,605	605	72	29.00	163	169	138	155	70	2.2	3.0	278.0	.460	.....

No. 18 stop.—At this time the engine began to weave badly. An external examination showed that the crank case was so badly cracked that further running was impossible.

## AVERAGE OF AVERAGES OF FULL THROTTLE RUNS.

	1,689	708	58	29.05	163	170	122	144	72	2.0	9.0	347.8	.505	8.4
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## AVERAGE OF AVERAGES OF RUNS AT PARTIAL THROTTLE.

	1,635	642	62	29.06	164	170	126	145	72	2.6	8.4	306.8	.479	8.2
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<sup>1</sup> Full throttle.

<sup>2</sup> Error in reading gasoline scales.

<sup>3</sup> Water leaked in No. 2R cylinder water jacket under cam-shaft housing.

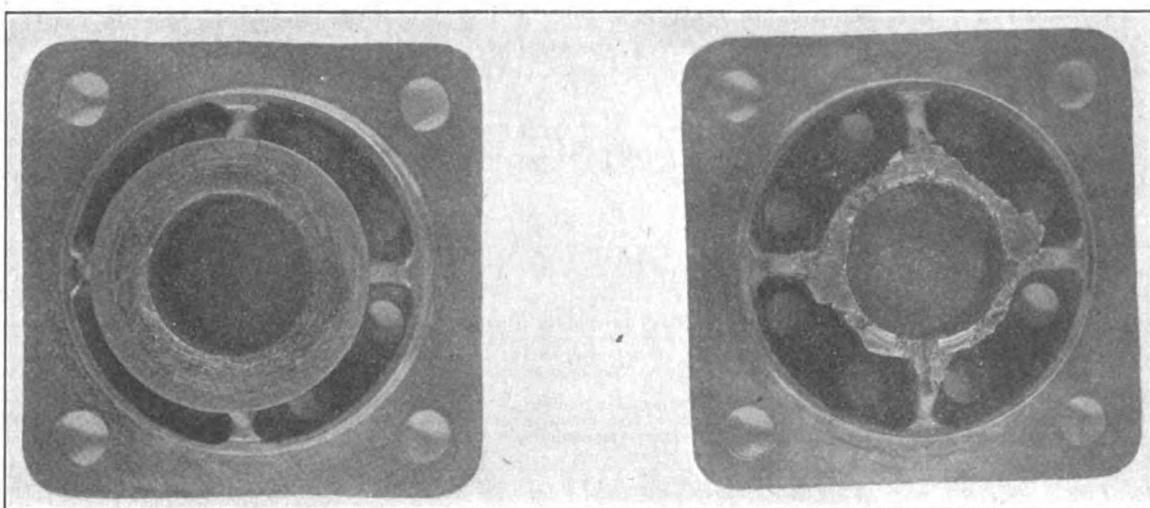


FIG. 7.—Camshaft drive-shaft lower bearings (upper) after preliminary runs on dynamometer.

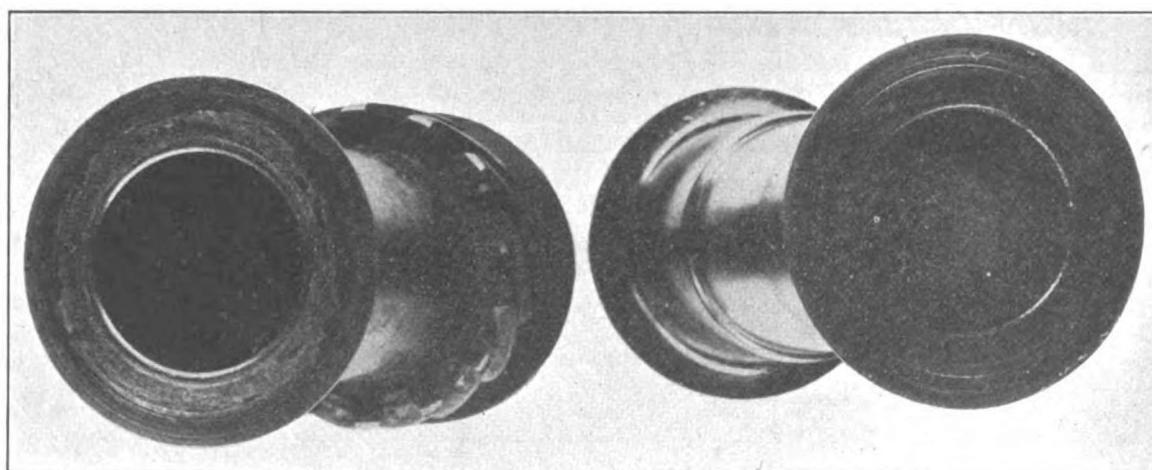


FIG. 8.—Lower center and lower side driveshaft spacing sleeves after preliminary runs on the dynamometer.

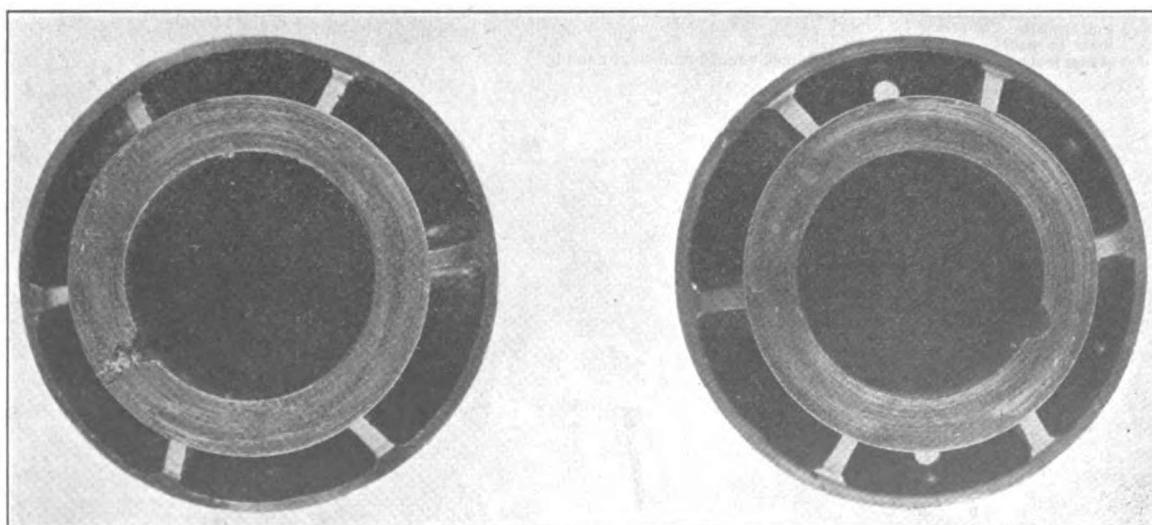


FIG. 9.—Camshaft drive-shaft bearings (lower) after preliminary runs on dynamometer.

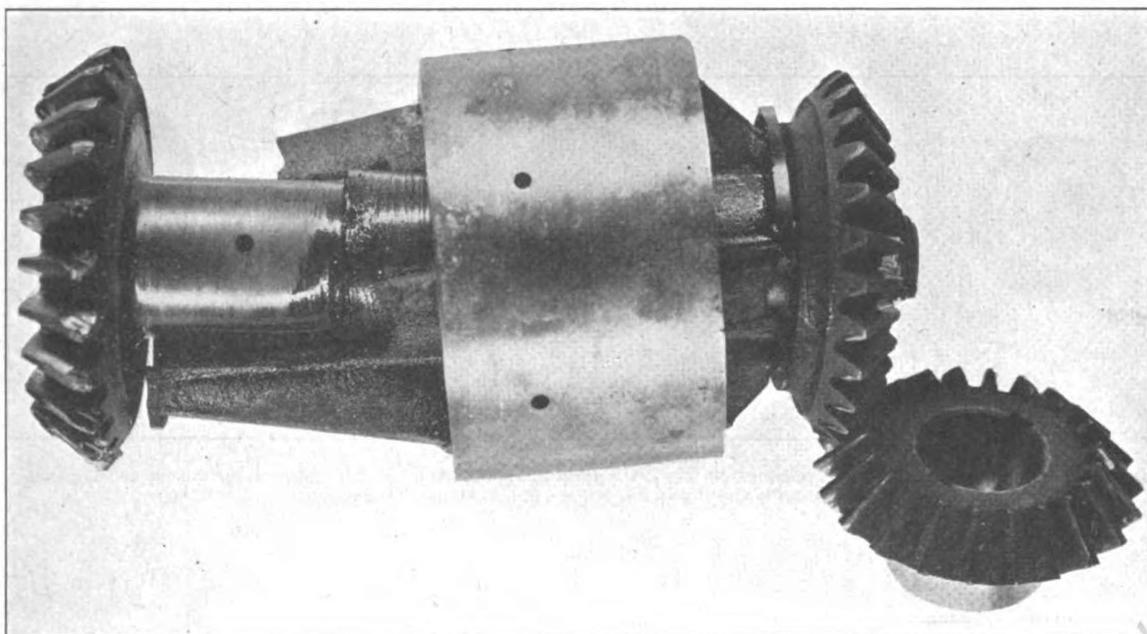


FIG. 10.—Burnt bearings oil and water pump gear assembly. This failure occurred during the preliminary runs on the dynamometer.

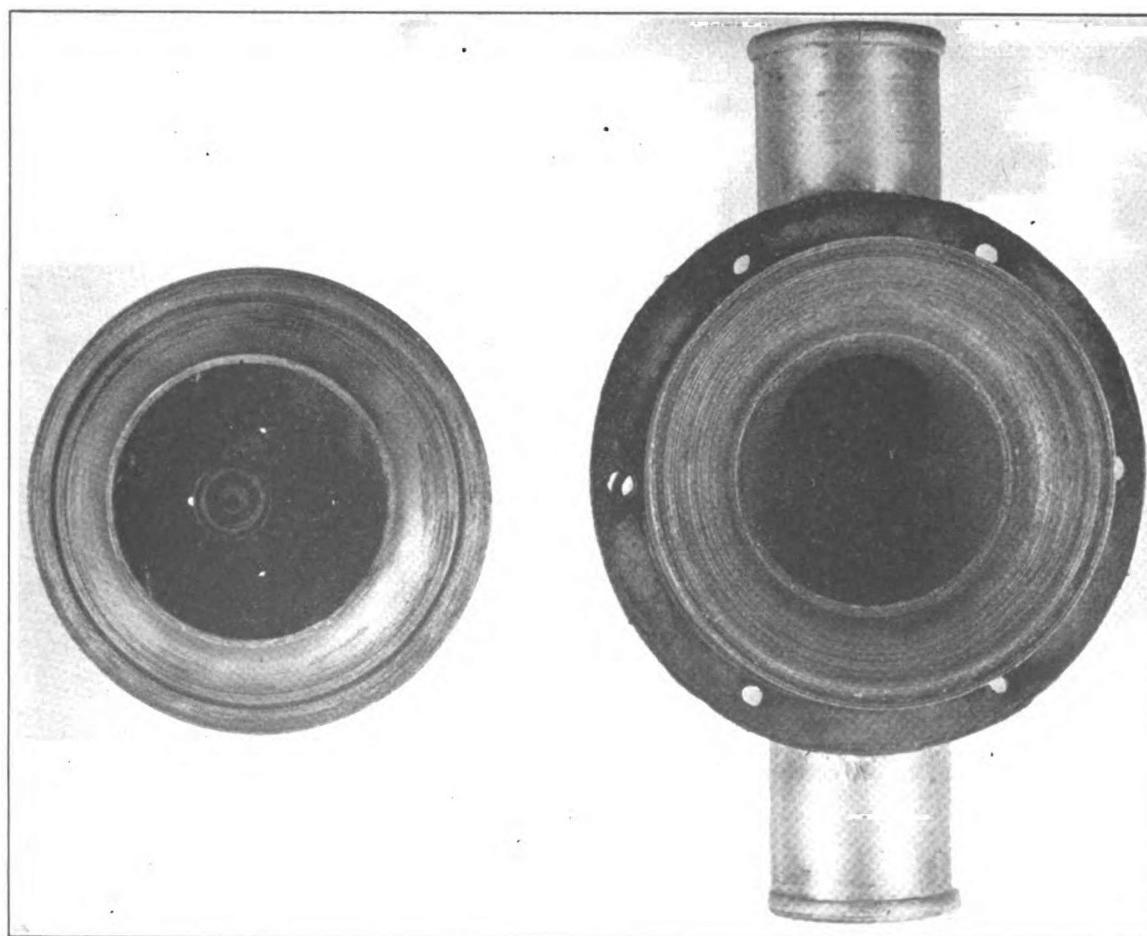


FIG. 11.—Water pump showing wear on impeller and lower casing. The wear developed during the dynamometer runs, but the pump was used during the torque stand after lignum vitae was substituted for the bronze button on the case.

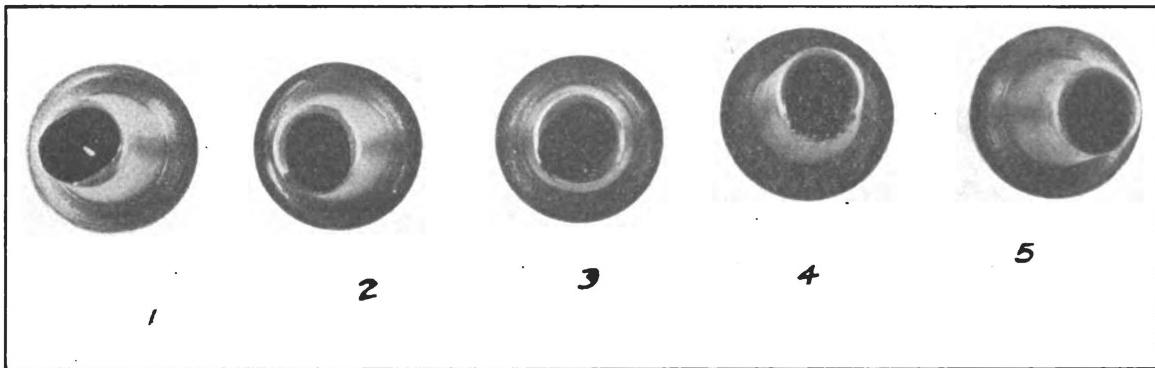


FIG. 12.—Worn valve guides after 35 hours running. No. 1 in this figure was removed April 28, 1921, after running 2 hours and 15 minutes. This is also typical of the valve guides replaced as indicated on page 17.

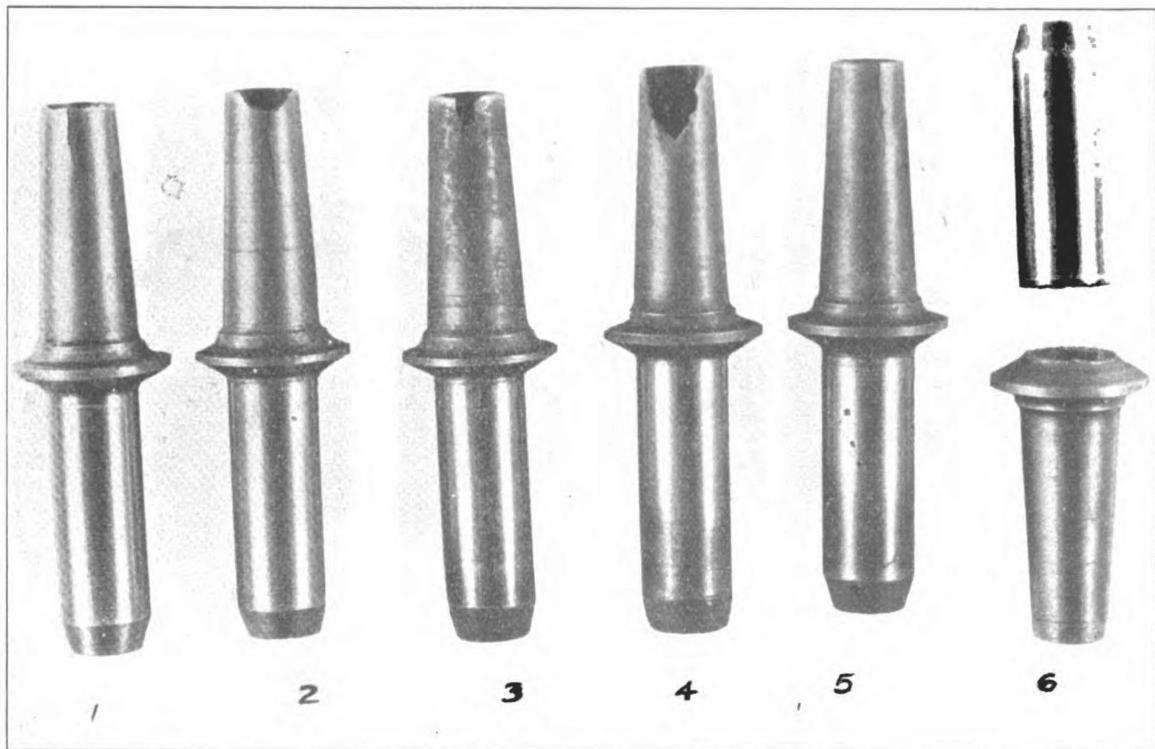


FIG. 13.—Worn valve guides after running 35 hours. No. 1 in this figure was removed April 28, 1921, after running 2 hours and 15 minutes. This is also typical of the valve guides replaced as indicated on page 17.

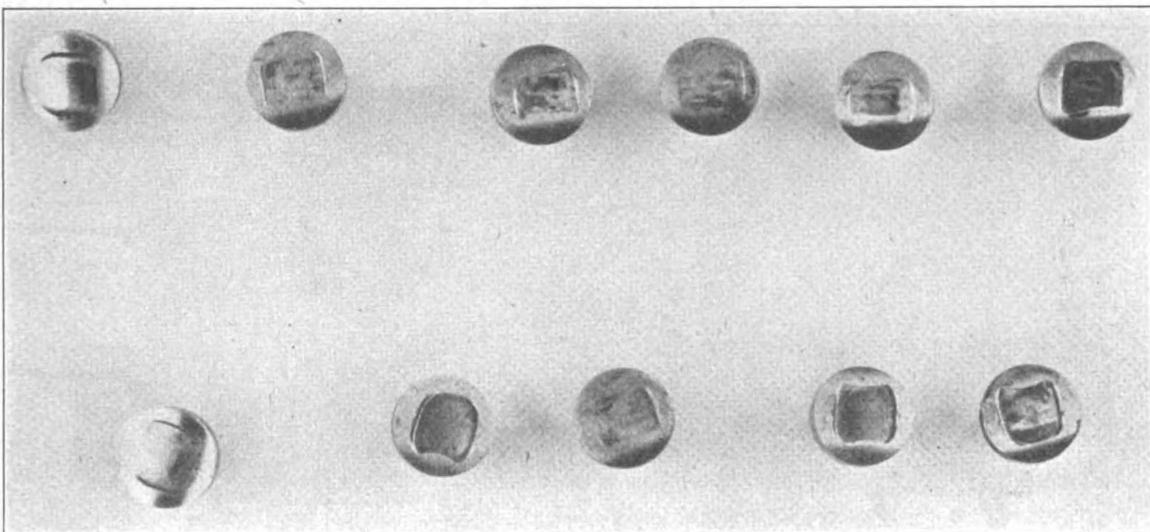


FIG. 14.—Worn valve tappets. These valve tappets were removed after running 38 hours.

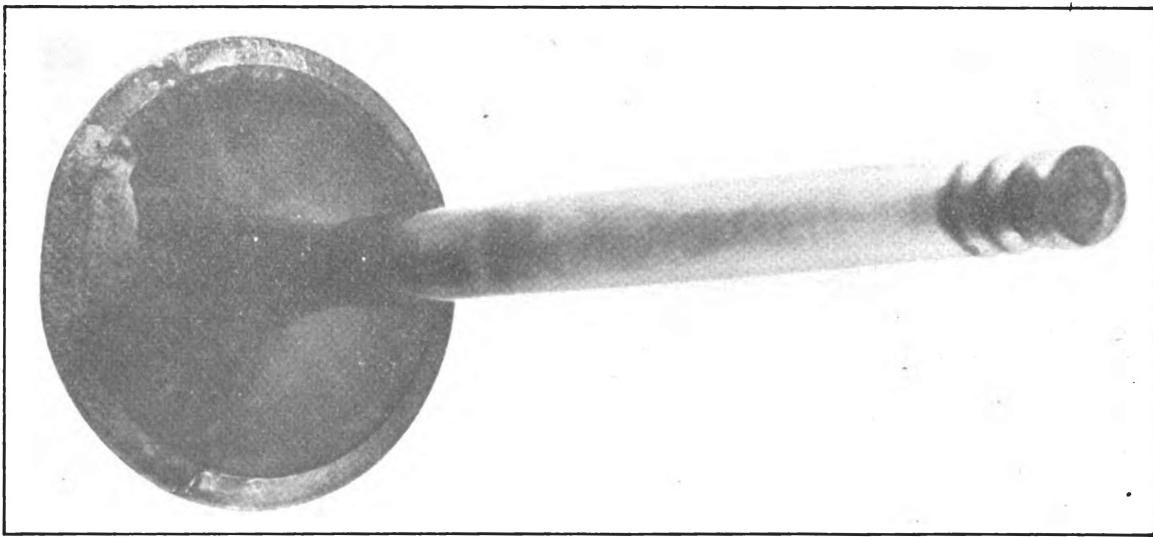


FIG. 15.—Burnt exhaust valve No. 6 L cylinder after running 38 hours.

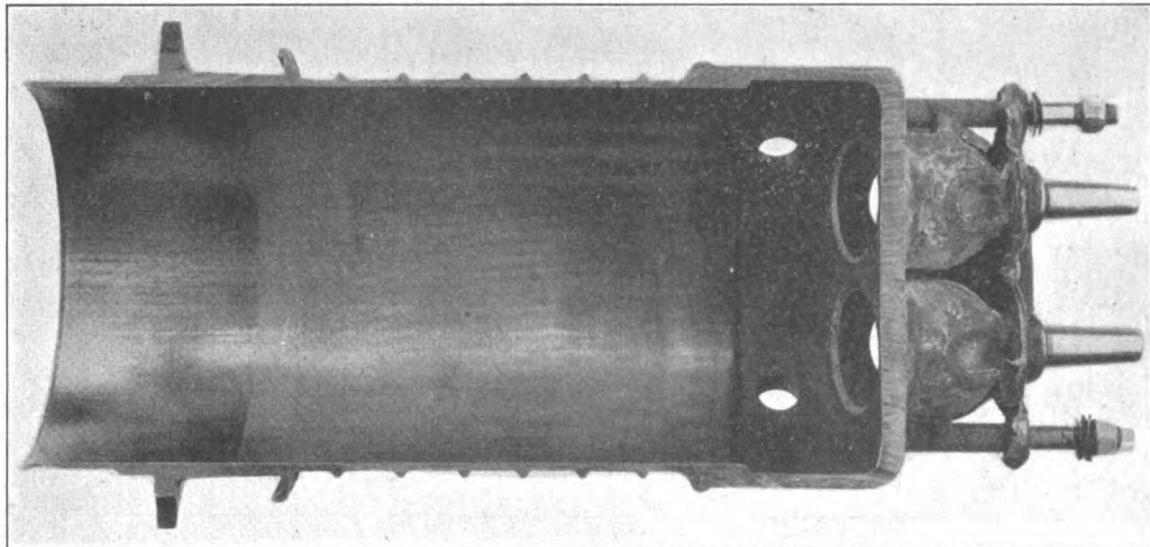


FIG. 16.—Sectional view of cylinder. A water leak developed in this cylinder after 40 hours and 15 minutes running at the junction of the cylinder head and barrel. The crack in the cylinder weld is not shown in this figure.

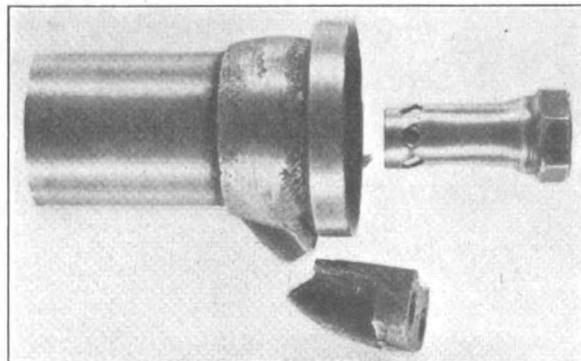
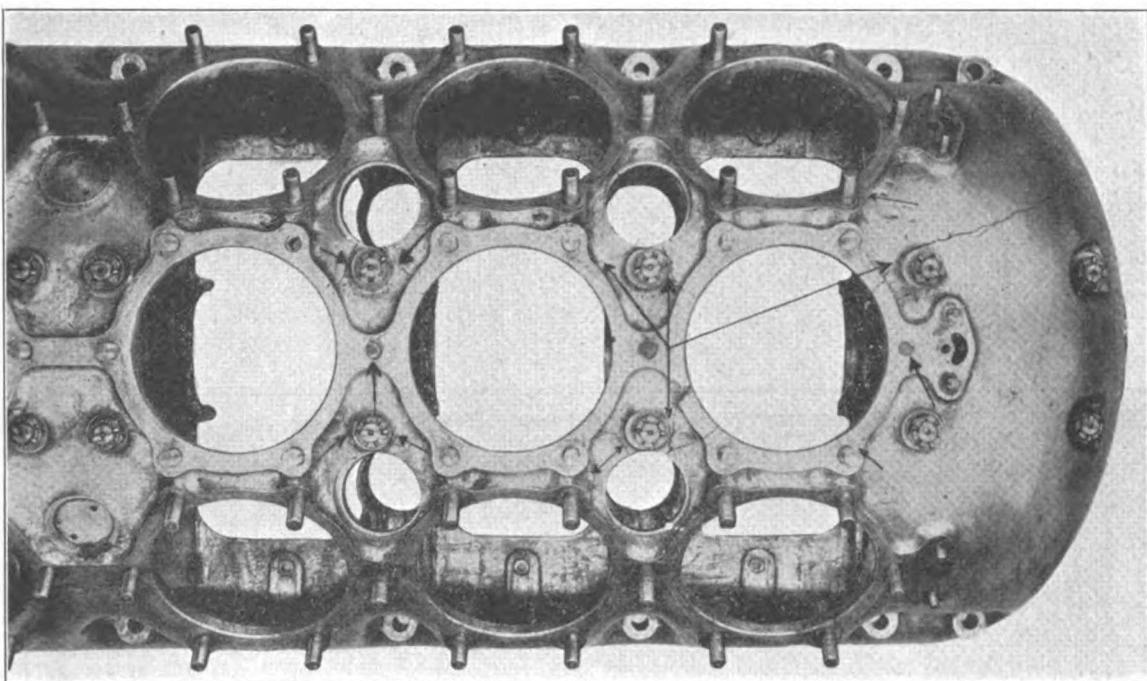


FIG. 17.—Typical failure of small venturi bracket and main discharge nozzle of front left carburetor. As indicated in the log of run two failures occurred during ninth five hour period.



Note fractures.

FIG. 18

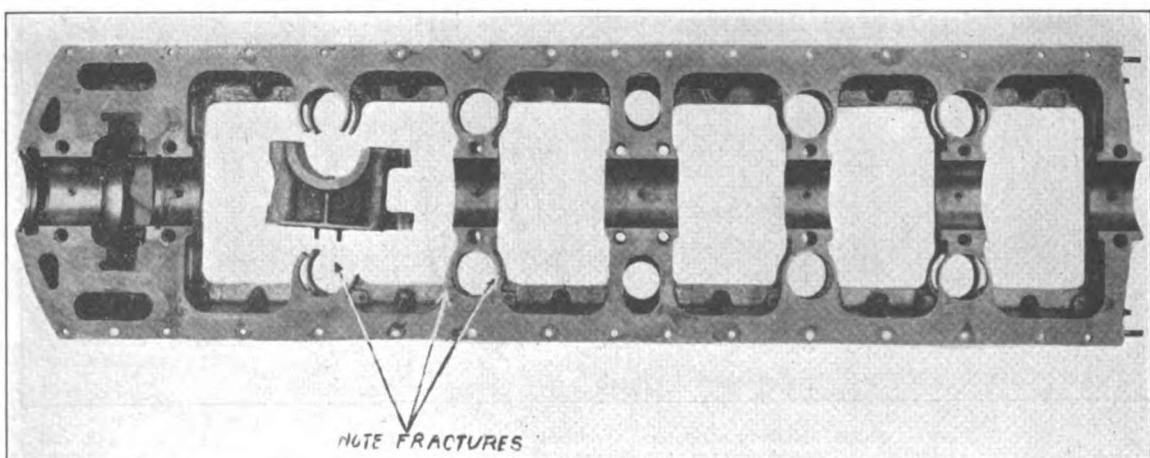


FIG. 19.—Lower crankcase after endurance run showing fractures.

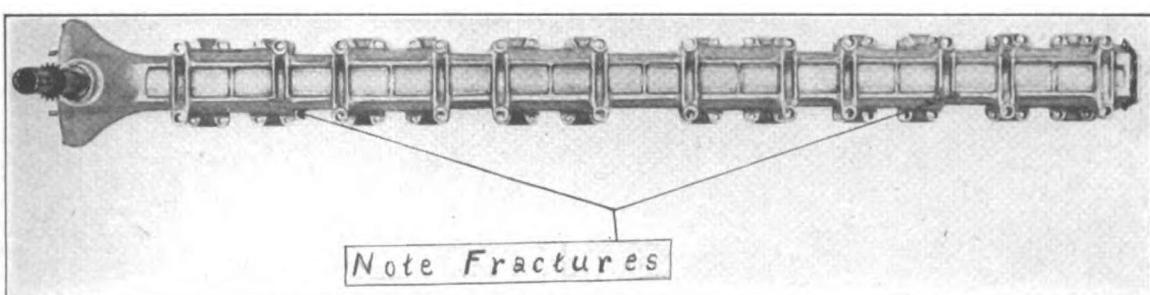


FIG. 20.—Camshaft housing showing typical fractures after endurance run. (Left bank.)

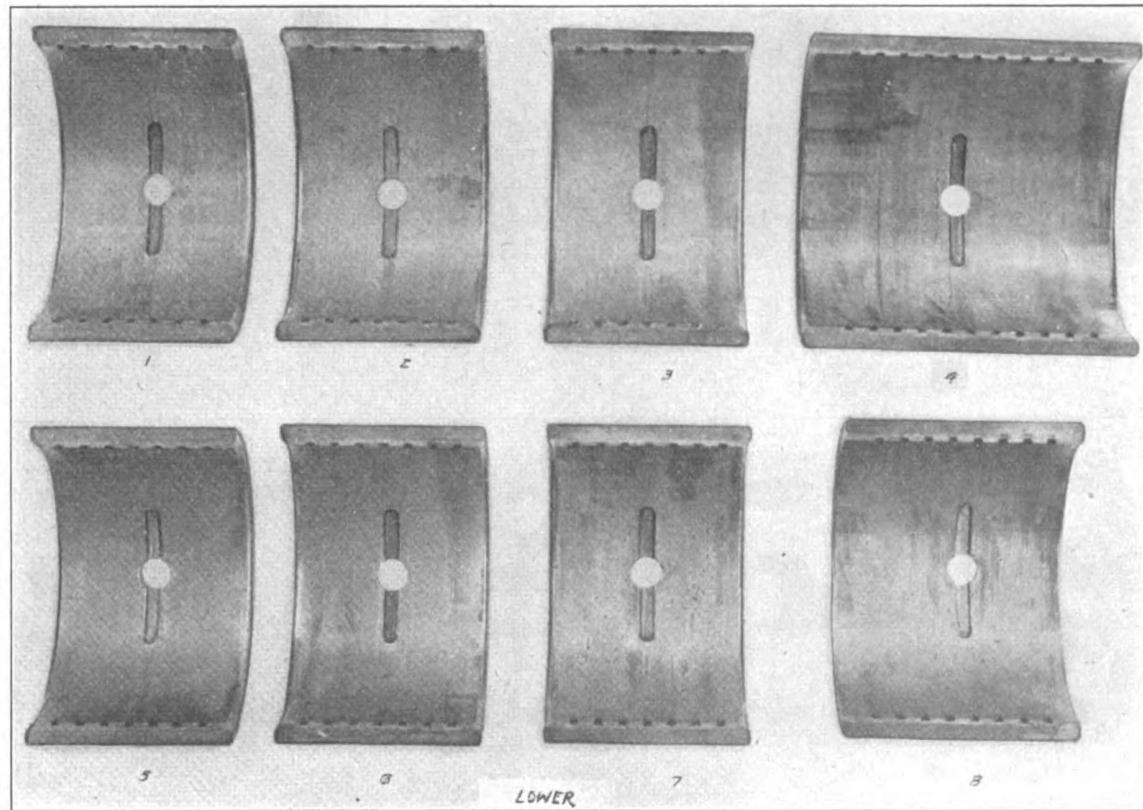


FIG. 21.—Lower main bearings. Condition after endurance run.

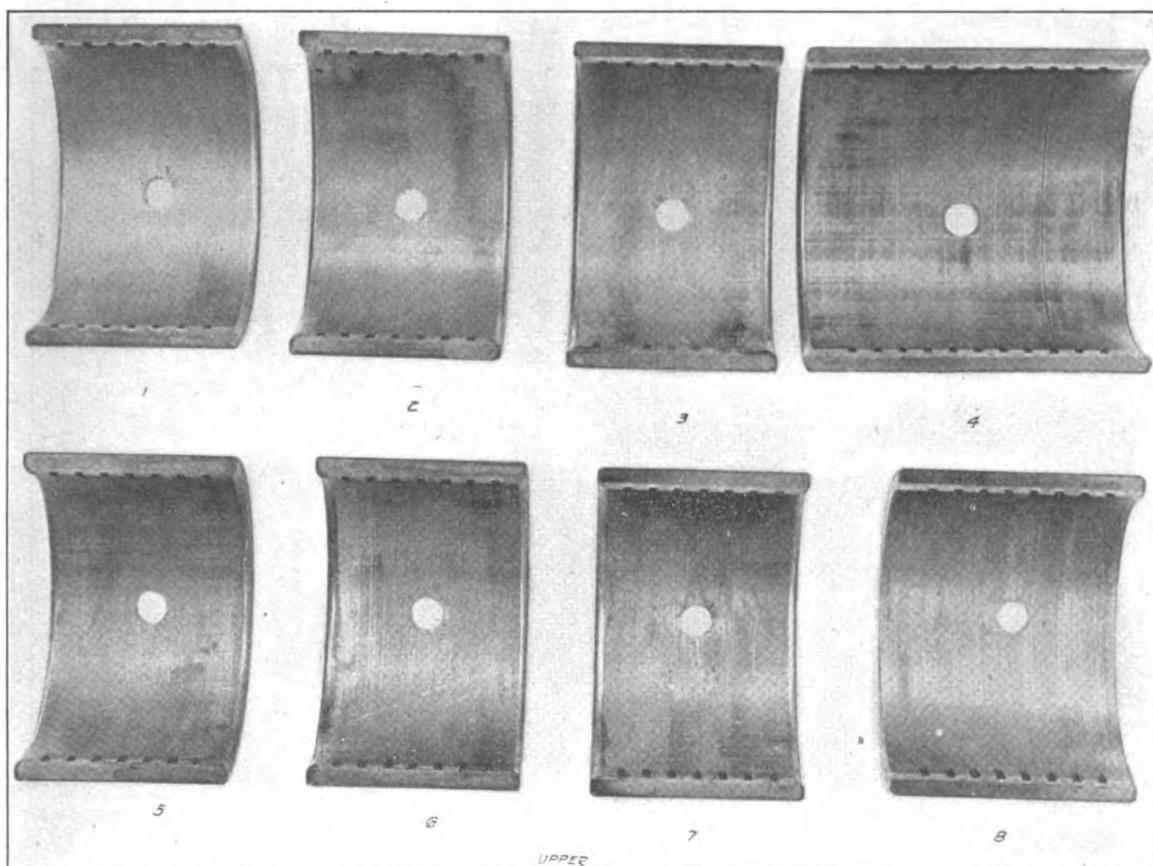


FIG. 22.—Upper main bearings. Condition after endurance run.

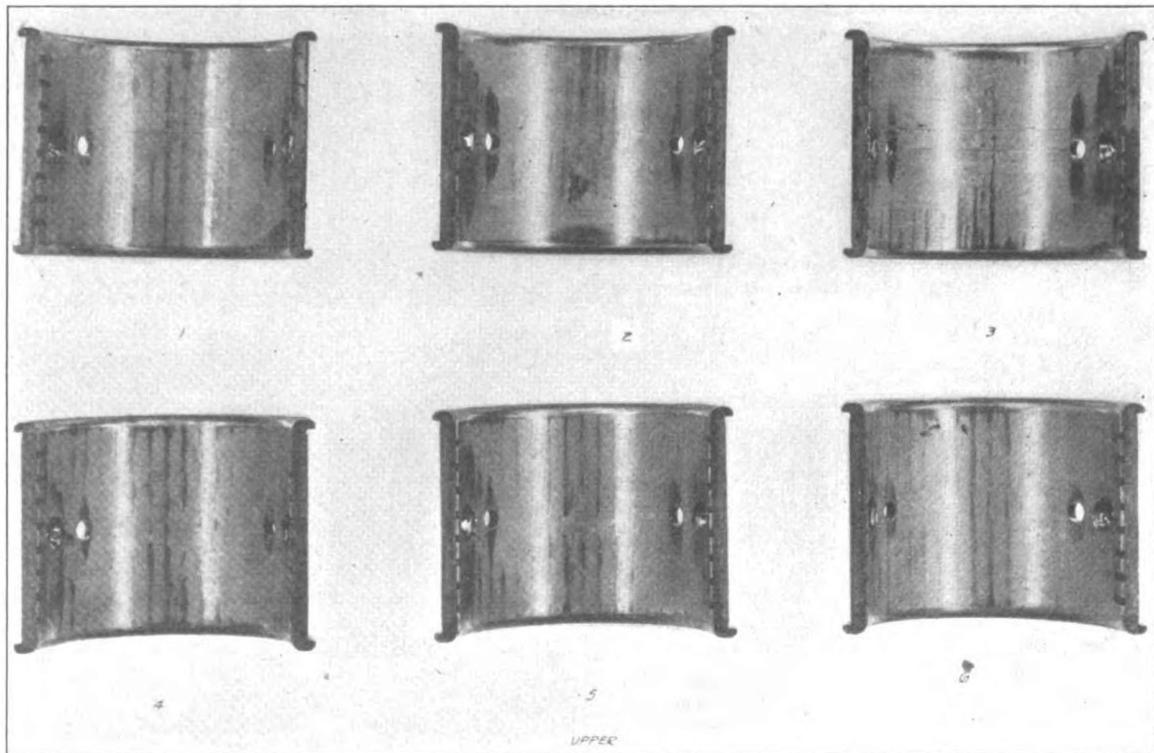


FIG. 23.—Upper connecting rod bearings after endurance run. Note original reamer marks made during assembly of engine.

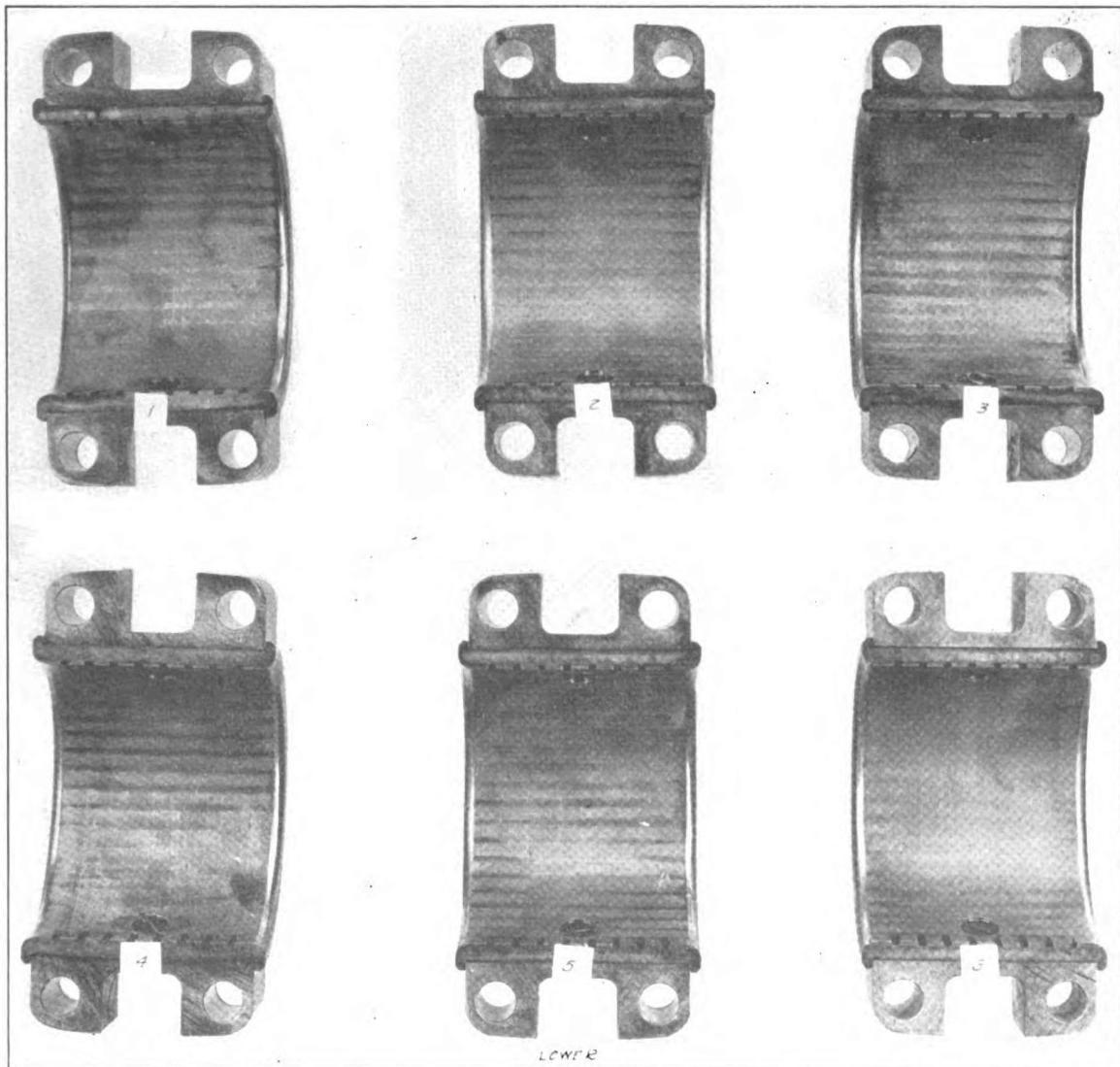


FIG. 24.—Lower connecting rod bearings after endurance run. Note original reamer marks made during assembly of engine.



FIG. 25.—Typical piston showing heavy carbon deposit.

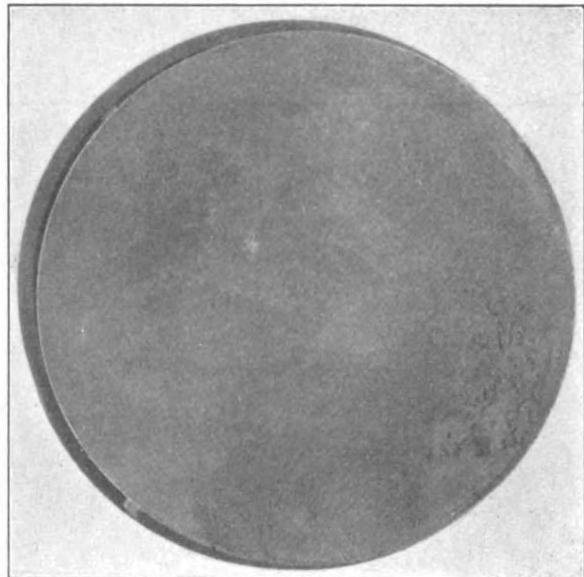


FIG. 26.—Typical piston showing average carbon deposit.

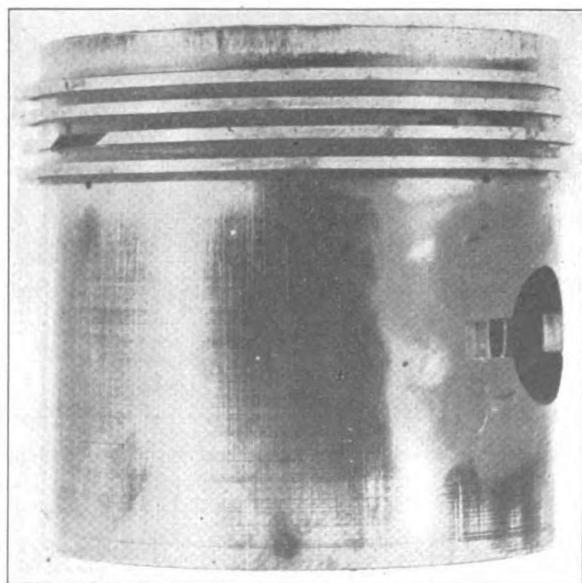


FIG. 27.—Typical piston showing wear on top land.

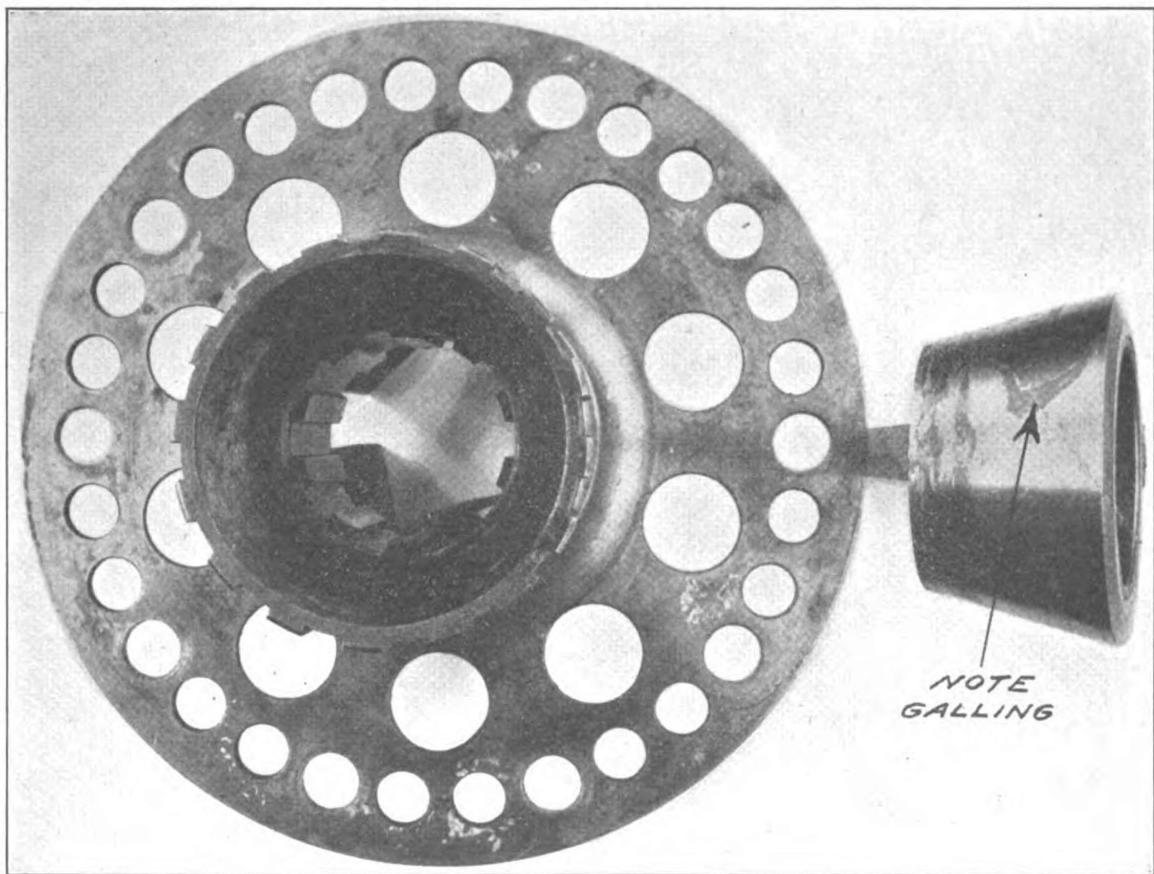


Fig. 28.—Propeller hub after endurance run.

